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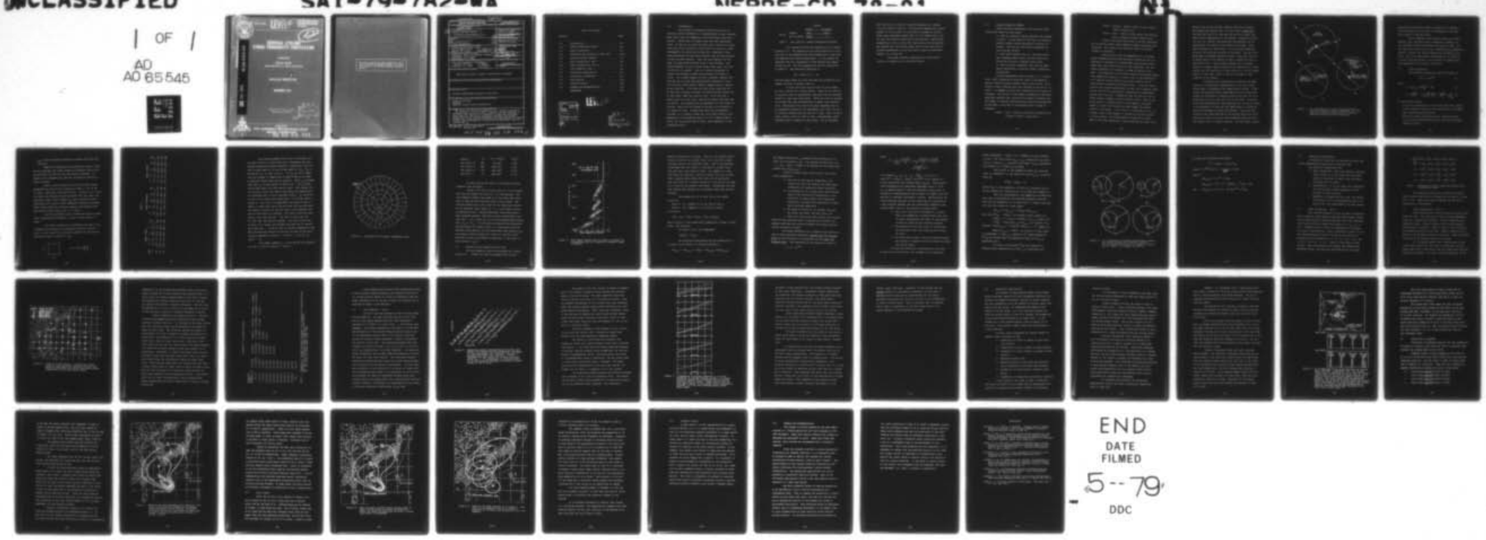

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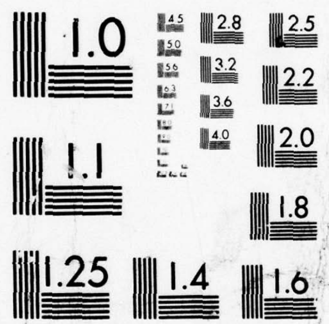

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TROPICAL CYCLONE STRIKE PROBABILITY FORECASTING

Prepared By:

Jerry D. Jarrell
Science Applications, Inc., McLean, Virginia 22102

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A system to infer the probability of a tropical cyclone's striking within an area, given a tropical cyclone forecast, is described. The results of a sequence of tests are presented, which indicate the system reasonably specifies the desired probability. Some envisioned operational applications of tropical cyclone strike probability information are described; some are illustrated.

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1.0 Introduction

The concept of recipients allowing for error in tropical cyclone forecasts is a standard part of Navy doctrine. Many thumb rules for computing a so-called danger area have evolved. These rules in general have two major weaknesses. First, if they are to cover the worst case, they are so large that ships with virtually no real threat are forced to evade. Consequently the rules have evolved as a compromise, thus under-protecting for the worst forecast case and over-protecting for the best forecast. They are only adequate for the range of cases whose forecast error is near average. The second weakness is that in using these thumb rules, the risk is difficult to assess. Thus it is almost impossible to compare the probable outcome from alternative courses of action. As a simple example of such a problem, suppose that each day you can take some precautionary measure at a cost of $100 which would prevent $2000 in damage should a typhoon strike that day. If we take our $100 action every day for 20 days and no typhoon strikes, we would have been better off to have never taken the action at all. So we see that a better plan is to wait until some threat exists and then take the action. This problem can be expressed in a loss table as follows: There are two courses of action: (1) do nothing or (2) spend our $100. In each case there are two possible outcomes: (1) a typhoon strikes (we lose either $2000 or $100 depending on the preceding action) or (2) a typhoon doesn't strike (we lose either zero or $100, again depending on the preceding action).

		Outcome	
		Strike	No Strike
Action	Prepare	\$100	\$100
	Don't Prepare	\$2000	0

Table 1. Loss table for typhoon preparation problem.

Let's suppose we know the probability of a typhoon striking is P. One approach to this type problem is to prepare only if the expected loss with preparation is less than the expected loss without preparation. In our example the expected loss with preparation is \$100 whether the typhoon strikes or not. But the expected loss without preparation is 2000 x P. The resulting inequality is

$$100 < 2000\ P \text{ or } P > .05$$

Thus we should spend our \$100 only when the probability of a typhoon striking is greater than 5%.

In real life there are all sorts of grey shades. One isn't faced with a single choice. There are an infinity of possible costs of preparation; often most are not possible because of lead time limitations. There are also all degrees of outcome from some inconvenience to almost total destruction. Additionally the loss of military equipment may not be represented simply by its replacement cost since its use to national defense would be lost for a time. Also, we don't place a dollar value on loss of life. Nevertheless, gross estimates may be adequate in many cases. We can estimate

that the cost of a sortie or evasive maneuvers of a vessel is on the order of $10,000. The potential damage from a major typhoon is on the order of $1 million to perhaps $5 million. These gross estimates suggest that if P is greater than 1% to 5%, then the evasive action may be the best bet. When strike probability is 10%, or even 25%, there can be little question. The problem with the present thumb rules is that they do not provide information to allow the user to know the difference between .1%, 1% and 10%.

This paper concerns computation of strike probability as a superior aid in decision making.

2.0 Strike Probability Theory

There are three fundamental facts that have been intuitively known for many years:

1) That all tropical cyclone forecasts are subject to error. If this were not the case, we certainly wouldn't bother issuing warnings at 6 hourly intervals. One for all time would be adequate for each tropical cyclone.

2) That some forecasts are, on a relative scale, easy (probable small error) and that others are relatively difficult (probable large error).

3) That the error components (E-W and N-S components) approximate a bivariate normal probability distribution.

A Naval Postgraduate School student, D. S. Nicklin (Capt. USAF) conducted an extensive study of Northwestern Pacific tropical cyclone forecast errors (see Nicklin, 1977). Nicklin's basic findings were also reported by Jarrell et al. (1977). In summary he found that indeed there are classes of forecasts. By the use of such simple parameters as latitude, longitude, maximum wind, direction and speed of movement and the number of tropical cyclones being forecast simultaneously by the JTWC, he was able to distinguish three classes of forecasts.

Class 1 Good: Likely to have below average error, unlikely to have a large error.

Class 2 Average: Equally likely to have either a large or small error.

Class 3 Poor: Likely to have larger than average error, unlikely to have a small error.

Nicklin also found the errors to be well described by a bivariate normal (each component normal) frequency distribution. This finding also held for each of the three classes of forecasts.

Prior to this time the assumption of a bivariate normal frequency distribution had been invoked for the construction of probability ellipses about each forecast point. These have some limited utility to the forecaster, but are almost impossible to interpret in terms of threat to the user. The assumption of a bivariate normal distribution specifies probability density at a point; that is the probability of a tropical cyclone being at any point relative to all other points including the forecast point. If we are interested in the typhoon being within an area (at a specific time), we can find that by numerically integrating the probability density over the area. Suppose we know the radius of 50 kt winds around a typhoon to be 75 nautical miles. Then at any point within 75 nautical miles of the typhoon, one would expect at least 50 kt winds, and even greater for points closer to the center. If you are at a fixed point (i.e., an island), then if the typhoon is located at any point within a 75 mile radius, you should expect at least 50 kt winds. Thus to find the probability of your receiving at least 50 kt

winds at one of the forecast times we need only integrate the probability density over a 75 mile circle around you. The fact that the 50 kt wind area may not be a circle only adds a minor complication to the problem. Usually the 50-kt (or 30-, 65-, 100-kt) wind areas will be described by two semicircles, the larger on the right of the track. Let's say the typhoon is moving west, its 50 kt winds extend 90 miles on the north and 60 miles on the south. You get 50 kt winds when the typhoon passes 90 miles to the south (you are 90 miles north of the center) or when it passes 60 miles to the north of you. Now we could integrate over two semicircles of unequal radius instead of two semicircles of equal radius, but the point here is that relative to you the larger area is to the south (left) or the mirror image of that relative to the typhoon.

Describing the distribution of winds by two semicircles is a simplifying approximation to the real distribution made to accommodate the communication system. A different and hopefully better approximation will be used here. Figure 1a illustrates a tropical cyclone with radii of 50 kt winds 100 nm on the right and 50 nm on the left. In figure 1b we have substituted an area described by a circle of radius 75 nm (average of 50 and 100) but whose center is offset by half the difference, 25 miles ($\frac{1}{2}$ (100-50)). Note that distances to the right and left of the cyclone center are still 100 and 50 nm but the along track discontinuities are gone. The overall area is reduced slightly. Our area about a point

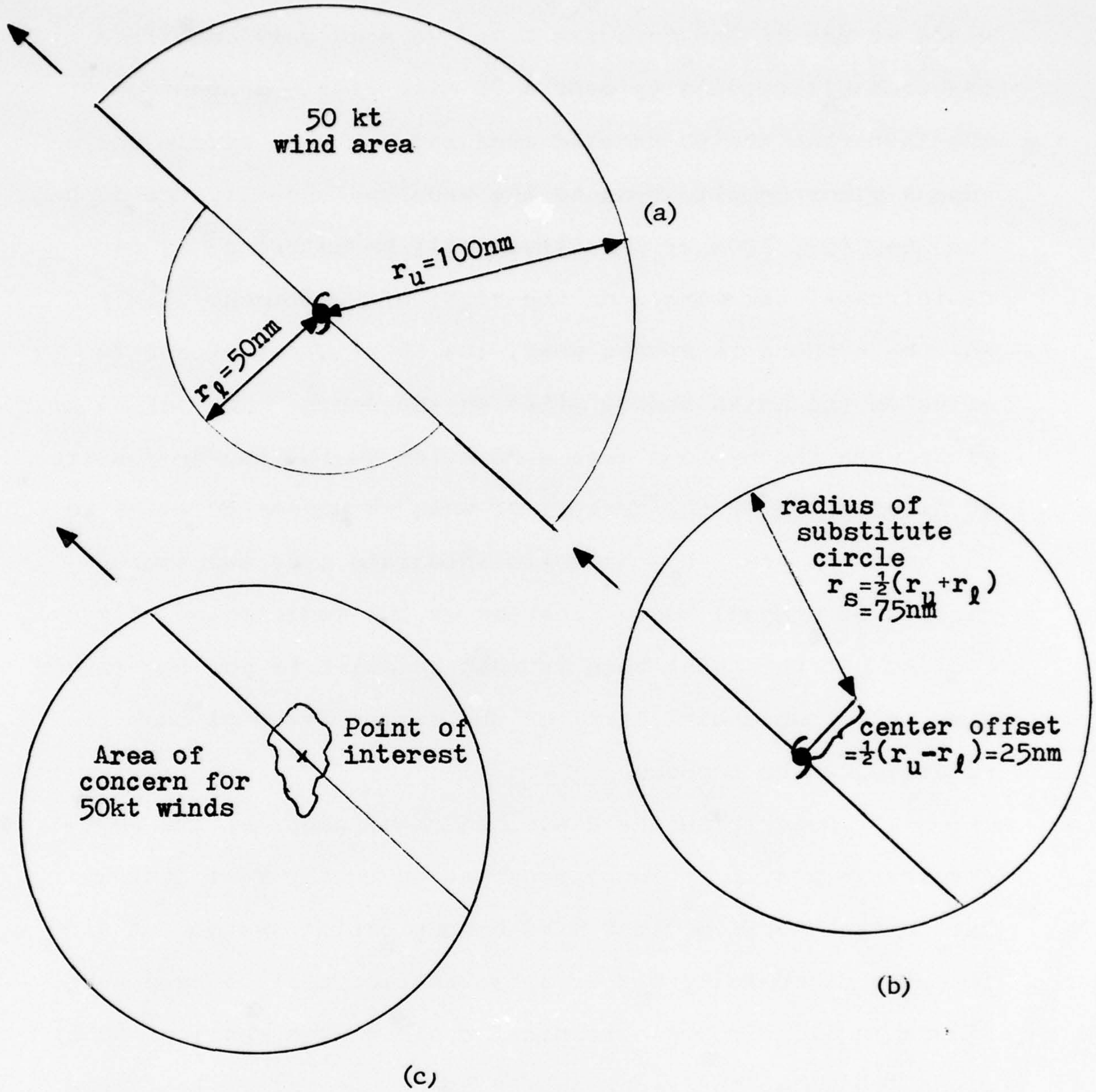


Figure 1. (a) Illustration of a 50 kt wind area about a tropical cyclone as might be reported in a forecast (b) substitute circle and (c) inverted substitute circle as area of concern.

would then be the mirror image of figure 1b, or figure 1c with the offset in a direction corresponding to the left with respect to forecast track.

Since typhoons do not usually strike on the GMT synoptic hour, you may be more interested in whether you are affected at some time between the forecast times. We can take care of that by not only integrating our probability density in space, but also by summing the probabilities in time. Now we can approximate the probability of those 50 kt winds occurring within a time interval by summing from the beginning of the interval to the end.

2.1 Space Integration

The bivariate probability density function is:

$$f(x,y) = He^{-G/2} \tag{1}$$

where

$$H = (2\pi\sigma_x\sigma_y\sqrt{1-\rho_{xy}^2})^{-1} \quad \text{and} \tag{2}$$

$$G = \left\{ \left(\frac{x-\bar{x}}{\sigma_x}\right)^2 - 2\rho_{xy}\left(\frac{x-\bar{x}}{\sigma_x}\right)\left(\frac{y-\bar{y}}{\sigma_y}\right) + \left(\frac{y-\bar{y}}{\sigma_y}\right)^2 \right\} \frac{1}{1-\rho_{xy}^2} \tag{3}$$

In the present context

x,y are the coordinates in miles east and north, respectively (negative values are west and south) of the forecast tropical cyclone position.

$\bar{x},\bar{y}$ are the mean E-W and N-S errors (nautical miles).

σ_x,σ_y are the standard deviations of E-W and N-S errors (nautical miles).

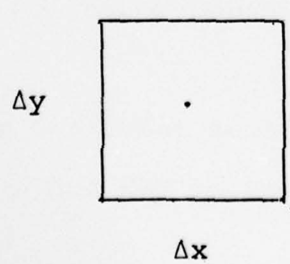
ρ_{xy} is the correlation coefficient between E-W error and N-S error.

These five constants are estimated by Nicklin (1977) and are available for three classes of forecasts (Good, Average and Poor) for the 24-, 48- and 72-hour forecasts. A common set of constants are used for the warning position or 0-hour forecast.

Table 2 gives values of the five bivariate normal parameters for each of the 3 groups at times: 0, 24, 48 and 72 hours. These were from 1966-75 data. Jarrell et al. (1977) has shown that forecast errors decreased over that time; consequently, these values (except ρ_{xy}) were reduced by 10% to approximate the current (1978) estimated forecasting accuracy. These values should be monitored annually and adjusted when they change significantly over 3 or 4 years.

The five parameters were interpolated using a second order interpolation polynomial to every 3 hours from 0-72 hours.

The actual integration is performed over small area increments by evaluating the probability density function f(x,y) at the centroid of the area increment and multiplying that by the area (in units of $\sigma_x \sigma_y$).



$$\Delta P = f(x,y)\, \frac{\Delta y}{\sigma_y}\, \frac{\Delta x}{\sigma_x}$$

Table 2

time	Group 1 (Good)					Group 2 (Average)					Group 3 (Poor)				
	$\bar{x}$	$\bar{y}$	σ_x	σ_y	ρ_{xy}	$\bar{x}$	$\bar{y}$	σ_x	σ_y	ρ_{xy}	$\bar{x}$	$\bar{y}$	σ_x	σ_y	ρ_{xy}
0	0.0	0.0	26.0	21.0	.0	0.0	0.0	26.0	21.0	.0	0.0	0.0	26.0	21.0	.0
24	−6.0	3.1	87.9	75.3	.121	−16.1	−5.1	119.4	96.0	.139	8.5	−3.1	129.6	118.4	.195
48	−15.0	4.1	195.9	151.4	.394	−19.4	−31.3	237.4	182.5	.259	19.2	15.6	258.7	223.0	.314
72	−14.4	2.2	309.6	235.4	.459	−8.1	−70.6	370.3	252.2	.340	17.0	27.5	368.4	302.5	.406

This process assumes that f(x,y) is constant over the small area or at least that f(x,y) represents the area average probability density function. Significant error begins to occur when Δx, Δy are on the order of $.5\sigma_x$, $.5\sigma_y$ or greater.(if $\Delta x = \Delta y$ when $\Delta x \, \Delta y$ is $> .25 \, \sigma_x \, \sigma_y$.) It is important for economy of computation to keep Δx and Δy as large as possible without sacrificing accuracy. Since σ_y is always less than σ_x, we have chosen to keep $\Delta x \, \Delta y < .20 \, \sigma_y^2$ which allows some margin for some special cases. With radius left (of forecast track) and radius right given, the computations are performed over a circle centered at $\frac{1}{2}(r_r - r_L)$ (positive is left of the track) with radius $\frac{1}{2}(r_r + r_L)$ as was shown in figure 1c. The circle is subdivided into rings as seen in figure 2, where each outer ring has twice the area and twice the number of sectors as the next inner ring; therefore the area of each sector is constant. The inner circle has area equal to the other sectors. The radii of the rings are $\sqrt{5}$, $\sqrt{13}$, $\sqrt{29}$, and $\sqrt{61}$ grid lengths. The entire circle has an area of 61π square grid lengths and there are 61 sectors each with area π. Since we want to minimize computation time while maintaining accuracy we use only as many of the outer rings as necessary to keep $\Delta A = (\Delta x)(\Delta y) < (.20) \, \sigma_y^2$, or $\Delta A/\sigma_y^2 < .20$.

For example suppose $\sigma_y = 75$ nm and we are integrating over a circle of radius R = 100 nm.

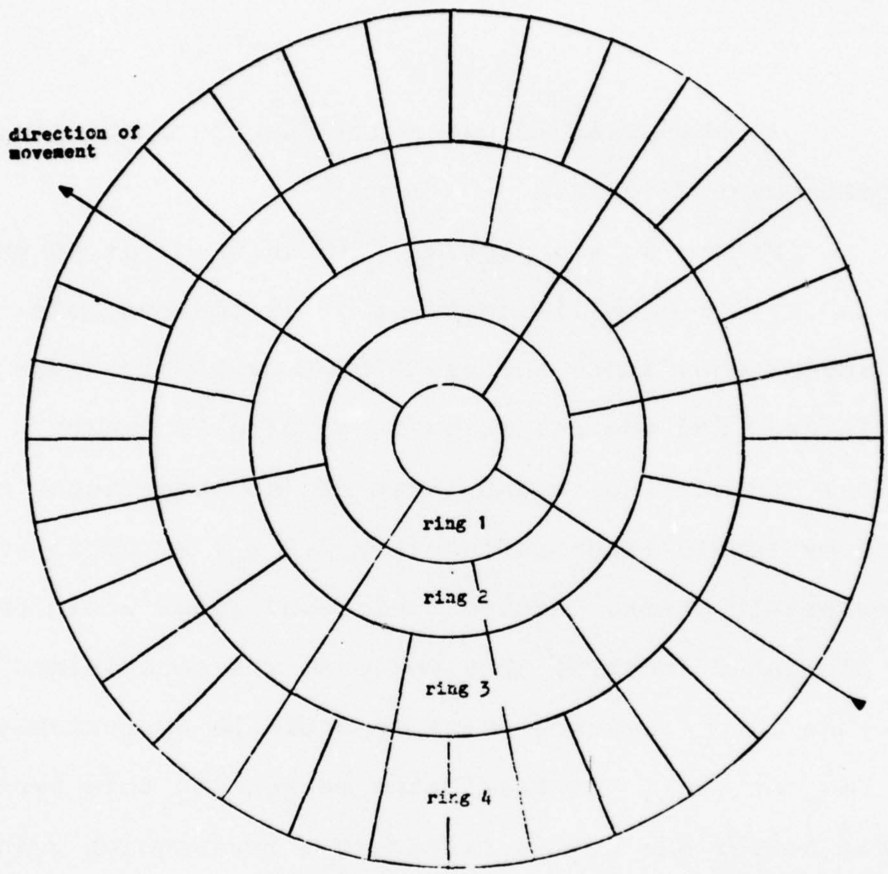


Figure 2. Illustration of circular integration grid.

Options	R_o	$\Delta A = \pi(R/R_o)^2$	$\Delta A/\sigma_y^2$
Use rings 1–4	$\sqrt{61}$	515 nmi^2	0.092
Use rings 1–3	$\sqrt{29}$	1083 nmi^2	0.193
Use rings 1–2	$\sqrt{13}$	2417 nmi^2	0.430
Use ring 1	$\sqrt{5}$	6283 nmi^2	1.117

In this case we use ring 3 as the outer ring and integrate over 29 points.

Figure 3 is a plot of R(in units of σ) as the ordinate and grid length (in units of σ) as the abscissa. The line segments indicate the range of R over which each outer ring is used and the resulting range of grid length. The vertical dashed line is the limit of "no significant error". For an extremely large radius ($R > 2.2\ \sigma_y$) we begin to pick up measurable error. Adding additional rings would entail some elongated sectors, thus while ΔA was constrained to be less than $.2\ \sigma_y^2$, either Δx or Δy could be appreciably greater than $.5\sigma_x$ or $.5\sigma_y$. At that point we abandon this system and instead center our offset circle on a rectangular grid with east–west grid spacing $\sigma_x/2$ and north–south grid spacing $\sigma_y/2$. Grid spaces totally outside the circle are ignored, those partially inside are included in proportion to the ratio of area inside to $\sigma_x\sigma_y/4$.

2.2 Summing Strike Probability Over Time

The time summation cannot be performed as a direct integration because in time the probabilities are not

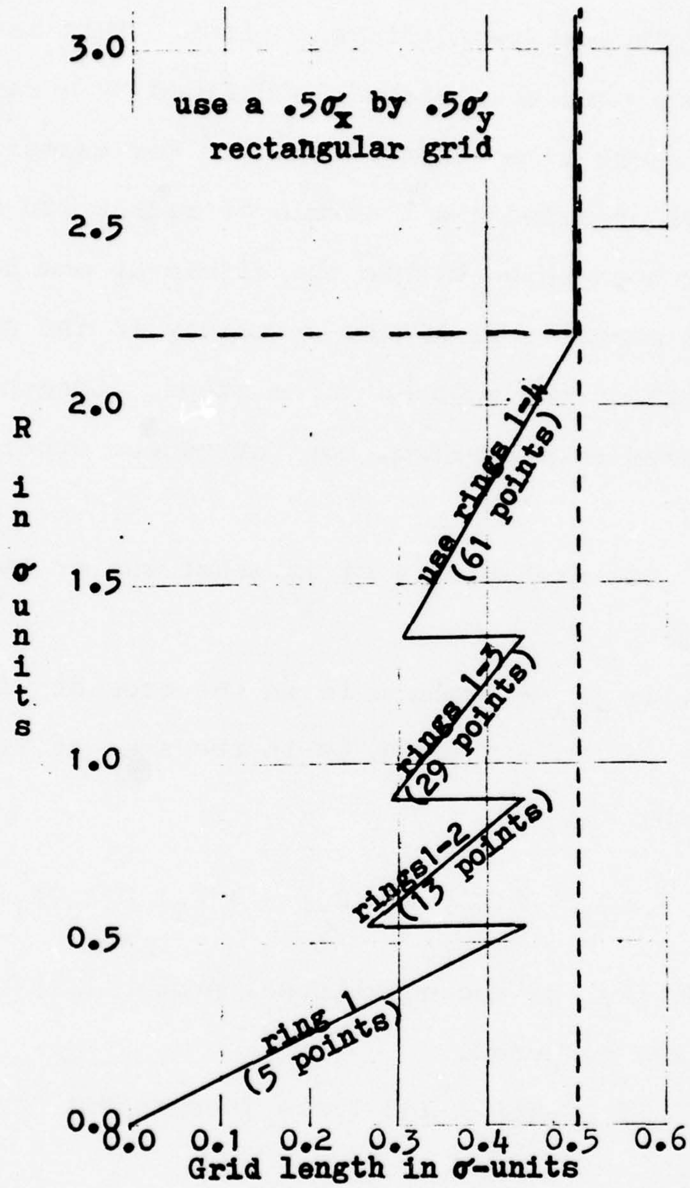


Figure 3. Grid length (square root of area of a sector) on integration grid as a function of radius of area of concern.

mutually exclusive as in space. That is, the cyclone cannot occupy two places at a single time, but it may well occupy the same place at two different times. This is particularly troublesome when the "place" is defined by a rather large area and short time steps are used. For example if 3 hour time steps are used and a circle of radius 100 n mi is used, then a typhoon being within the circle at one particular time also means it is almost certainly in the circle at either one or both of the adjacent time steps. Lengthening the time step reduces this problem, but introduces other more serious problems.

The probability of at least one or two events occurring

Event 1: E_1 – Typhoon is in the area at Time 1

Event 2: E_2 – Typhoon is in the area at Time 2

is given by

$$P(E_1 + E_2) = P(E_1) + P(E_2) - P(E_1)\ P(E_2|E_1)$$

where $P(E_2|E_1)$ is the conditional probability of Event 2 given Event 1 has occurred.

If Events 1 and 2 are independent

$$P(E_2|E_1) = P(E_2)\ .$$

The recursive relationship for the probability of at least one of several (n) events occurring is

$$P(E_{1,n}) = P(E_{1,n-1}) + P(E_n) - P(E_{1,n-1})\ P(E_n|E_{1,n-1})$$

The compact notation $E_{1,n}$ represents the occurrence of at least one of Events E_1, $E_2,\ldots,E_n$ usually written $P(E_1 + E_2, + \ldots, E_n)$. What is needed is an estimate of the conditional probability $P(E_n|E_{1,n-1})$.

There are three factors which affect this conditional probability.

1) The size of the area of integration, the greater the size, the greater the conditional probability of consecutive events occurring.

2) The probability of a single event occurring, because of the particular circumstances in the definition of these events, the conditional probability increases with probability of each event occurring separately.

3) The speed of motion by (or through) the area. The slower the speed, the more likely any event will occur given that another has occurred.

There are many possible ways to approach this problem; the approach used here has intuitive appeal and produces statistically acceptable results.

The single probability of a typhoon being within an area of some particular dimensions <u>removed from the forecast point</u> can be converted to an equivalent ellipse <u>about the forecast point</u>. The dimensions of the ellipse are given by

$$P = 1 - e^{-c^2/2}$$

where

$$c^2 = \frac{1}{1-\rho_{xy}^{2}}[(\frac{x-(x_F+\bar{x})}{\sigma_x} - 2\rho_{xy}(\frac{x-(x_F+\bar{x})}{\sigma_x})(\frac{y-(y_F+\bar{y})}{\sigma_y})$$

$$+ (\frac{y-(y_F+\bar{y})}{\sigma_y}))^2]$$

If we assume $\rho_{xy} = 0$, $\sigma_x = \sigma_y = \sqrt{\sigma_x \sigma_y} = \sigma$, $\bar{x} = \bar{y} = 0$ then $c^2\sigma^2 = (x-x_F)^2 + (y-y_F)^2$, and $c^2\sigma^2$ is the radius of a circle centered on the forecast point (x_F, y_F). These simplifying assumptions are considered acceptable since ρ, $\bar{x}$, $\bar{y}$, σ_x, σ_y change slowly in time and equivalent errors occur in consecutive transformations and we expect to compare only consecutive or adjacent "equivalent" circles. Qualitatively the overlap between adjacent circles (which may be visualized as a Venn diagram) behaves like the conditional probability described above; that is, the overlap is greater when:

a) The size of the area of integration is large; hence the probability of being within that area is large, consequently the radii of the adjacent circles are large and the overlap increases.

b) The probability of either event is large—thus the equivalent radii are large and the overlap is large.

c) The storm moves slowly, thus the distance between the centers of adjacent circles is small and hence the overlap large.

We treat the probability represented by the areas of each of the two circles, not included in the overlap as

being independent. Figure 4 is a schematic of such adjacent circles. The circle about (x_{n-1}, y_{n-1}) represents the probability of Event $E_{1,n-1}$ and the circle about (x_n, y_n) represents the probability of Event E_n occurring.

The portion of the probability Event E_n occurring which is independent of the cumulative event $E_{1,n-1}$ is approximated by

$$P^*(E_n) = P(E_n) - \Delta P$$

where $P(E_n)$ is the probability of Event E_n occurring, and ΔP is the probability represented by the overlap area (figure 4.a).

With this approximation, the summation of probability over time is performed by the following recursive relationship for the probability of at least one of n events occurring (at least one strike in n time steps):

$$P(E_{1,n}) = P(E_{1,n-1}) + P^*(E_n)(1-P(E_{1,n-1})$$

Note that $P^*(E_n) = P(E_n)$ if no overlap occurs (figure 4.b)

$P^*(E_n) = 0$ if E_n is a subset of $E_{1,n-1}$, (figure 4.c)

$P^*(E_n) = P(E_n)-P(E_{1,n})$ if $E_{1,n-1}$ is a subset of E_n

and that $P(E_n|E_{1,n-1}) = (P(E_n)-P^*)/P(E_{1,n-1}) + P^*$ (Figure 4.d)

When $P(E_{1,n-1})$ is small, the portion of $P(E_n)$ which is independent of $P(E_{1,n-1})$ appears to be underestimated by $P^*(E_n)$ as defined above and approaches $P(E_n)$ as $P(E_{1,n-1})$ approaches zero.

To correct this problem $P^*(E_n)$ was adjusted to approach $P(E_n)$ exponentially as $P(E_{1,n-1})$ approaches zero

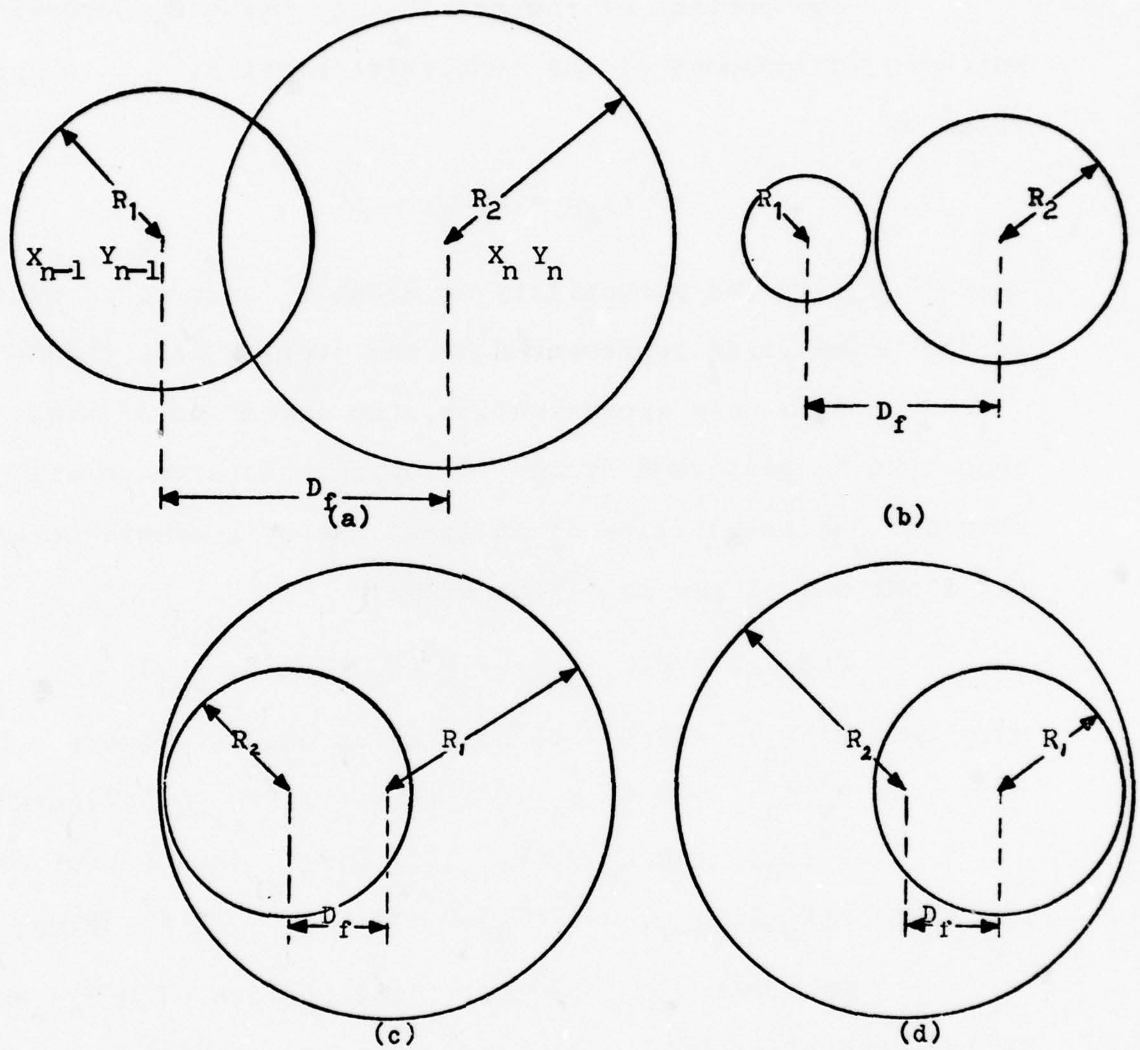


Figure 4. (a) Illustration of overlap area between consecutive strike probability forecasts (events) (b) no overlap (c) event 2 is a subset of event 1 and (d) event 1 is a subset of event 2.

by using the following relationship

$$P^{**} = kP(E_n) +)1+k)\ P^{*}(E_n)$$

where $k = e^{aP(E_{1,n-1})}$, $a = \frac{\ln(.5)}{0.05} = -13.86$

Thus if

$$P(E_{1,n-1}) = 0,\ P^{**} = P(E_n),$$

$$P(E_{1,n-1}) = 0.05,\ P^{**} = \tfrac{1}{2}(P(E_n) + P^{*}(E_n)),\ \text{and}$$

for $\quad P(E_{1,n-1}) \geq 0.17$, $k < 10\%$ and $P^{**} \doteq P^{*}(E_n)$

3.0 Testing and Test Results

A hierarchy of tests was set up where the most sensitive computations would be put to rigorous test.

The sensitive computations are:

a) Space integration: While the method is theoretically sound, it is not clear that the proper amount of precision is used in that the space grid might be too coarse.

b) Interpolation: It is not clear that interpolating the bivariate normal parameters and the forecast in time is valid.

c) Summation of probability over time: The particular method is only an approximation and it is unclear that this approximation is close enough.

3.1 Space Integration: Test 1

This test was designed to test the space integration over a range of values against known published values. Tables such as those given by Burington and May (1953) are available for circular bivariate normal distribution ($\sigma = \sigma_x = \sigma_y$, $\rho = 0.0$). Probabilities are given for combinations of R(radius of circle in multiples of σ) and d (distance of center of circle from distribution center $\bar{x}$, $\bar{y}$ also in multiples of σ). Integration was performed for R = 0.0, 0.2, 0.4,.. 3.0 σ and d = 0.0, 0.2, 0.4, .., 3.4 σ. Table 3 lists some of those results. Where differences exist between the computed and published values, the different published digits are shown.

R/σ	d/σ = 0.0	1.0	2.0	3.0	3.4
0.2	0.020	0.012	0.003	0.000	0.000
	4	7			
1.0	0.397	0.268	0.082	0.011	0.004
	5	1	8	4	6
2.0	0.866	0.734	0.399	0.112	0.054
		7	0	5	
3.0	0.989	0.954	0.793	0.438	0.289

Table 3. Comparison of space integrated probabilities vs published values.

The maximum difference was $\pm$ 0.006 and occurred near the point just before we change from 3 rings to 4 rings (R/σ = 1.2). These test results indicate the the space integration is satisfactory.

3.2 Time Interpolation: Test 2

Tests two and three involve the use of actual forecasts for 1976. For both tests a series of 40 geographical points in 4 groups were selected. Figure 5 shows the geographical points. Those of Group 0 are 10 actual bases or other points of interest. Those of Group E are 10 points in the southeast portion of the area. Those of Group W are 10 points in the southwest portion of the area. Group N consists of points on the northern portion of the area.

If a tropical cyclone had a closest point of approach (CPA) within 500 nm of one of the points, all forecasts made within 4 days before and three days after CPA were saved and considered. For test 2 the test parameter is the

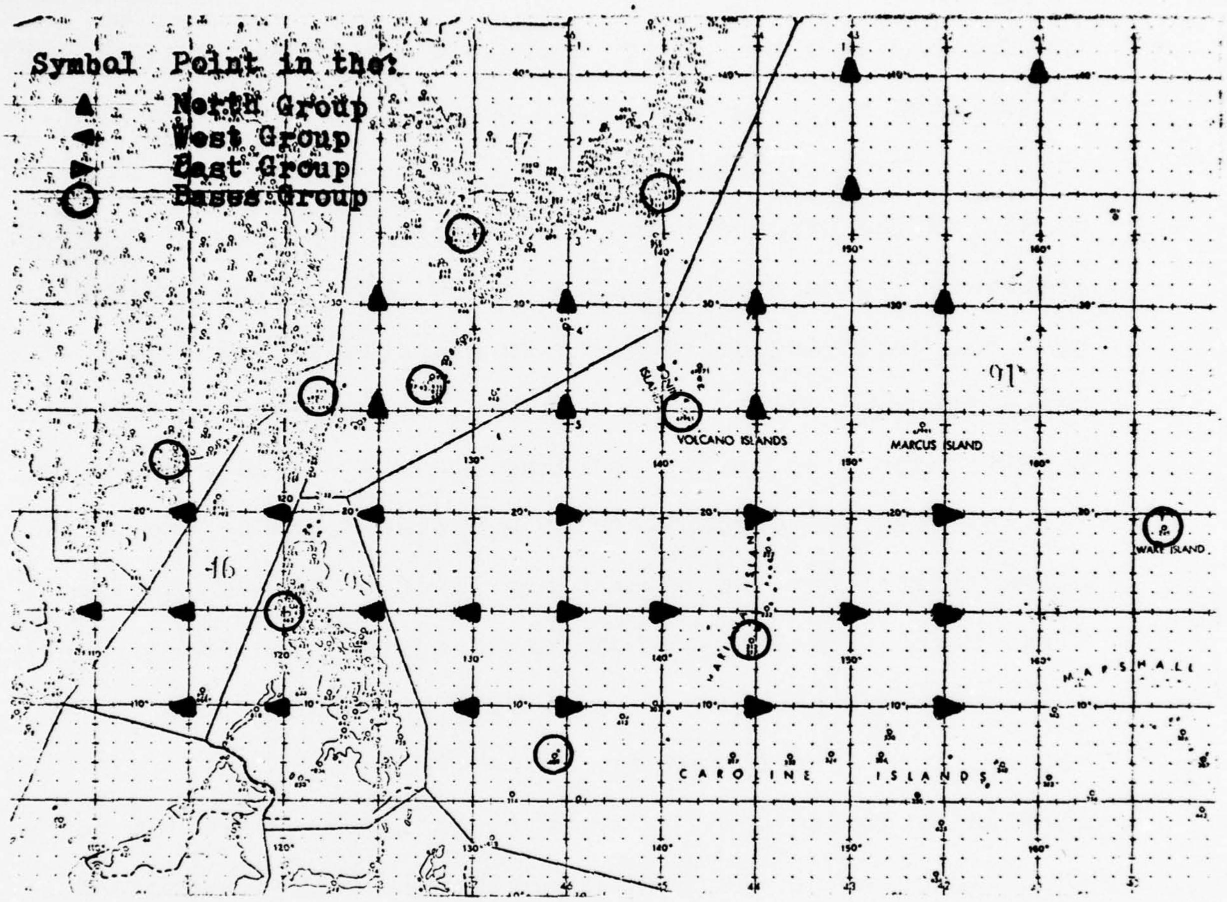


Figure 5. Location of Test Points: 0 points are actual bases or other points of interest; ▲ are of the northern group; ◄ points are of the western group; and ► points are of the eastern group.

probability of the cyclone being located within a test area about the point at 12 hour intervals from forecast time to 72 hours later (or longest forecast made if less than 72 hours). The probability of being within the test area at time zero was used as verification of earlier forecasts. The test area was defined as a circle of radius 62.5 nm offset 12.5 nm left of the test point relative to forecast direction of motion.

Table 4 summarizes the results of test 2. The predicted strike probabilities were classed into the 5% class intervals listed on the left. In the body of the table entries give the verifying average strike probability and number of cases for each class. The verifying average was tested for significance (.05 level) assuming a binomial distribution of strikes with the probability of a strike given by the upper class limit, then the lower class limit. The mean of the first group (0—4.5%) was not tested against the lower boundary (0%) since any non—zero average outcome would appear to be significant. The symbol (↓) means the average value was significantly lower than the upper class limit, while (A) means the average value was significantly above the lower class limit. There were <u>no</u> cases where the average value was significantly either above the upper limit or below the lower limit. Note the over 55% group at 12 hours was tested against the single mean predicted strike probability (60.0%). The general small size of these "instantaneous" strike probabilities simply underscores the current uncertainty in tropical cyclone forecasting.

Frequency of verifying strikes

Predicted Strike Probability	12-hours	24-hours	36-hours	48-hours	60-hours	72-hours
0– 4.5	0.1(5524)↓	0.3(4703)↓	0.7(3976)↓	0.9(3516)↓	1.5(2943)↓	2.0(2373)↓
4.5– 9.5	4.4(123)	8.7(210)[A]	6.7(320)	9.1(182)	6.6(47)	
9.5–14.5	8.0(53)	10.0(112)	8.8(51)			
14.5–19.5	19.4(40)	12.5(56)	23.2(4)			
19.5–24.5	27.6(33)	15.1(18)				
24.5–29.5	29.7(34)	26.2(13)				
29.5–34.5	30.2(18)					
34.5–39.5	54.7(4)					
39.5–44.5	35.3(6)					
44.5–49.5	57.9(5)					
49.5–54.5	42.8(4)					
>54.5	89.2(4)					

Table 4. Frequency of verifying strikes (percent) as a function of predicted strike probability. Number of cases is shown in parentheses.
(A) any value sig above lower class limit
(↓) any value sig below upper class limit

Since probabilities derived from interpolated values of the bivariate normal parameters and forecast positions at 12, 36 and 60 hours appear to verify no differently than the known "estimates" at 24, 48 and 72 hours, we conclude the interpolation scheme is satisfactory.

3.3 Time Summation: Test 3

The third test was designed to test the time probability summation. The same data was used as in test 2 but now the time summed probabilities for time intervals in multiples of 12 hours (i.e. 0–12, 0–24, .., 0–72 hours) were estimated. The verifying probability was taken to be the maximum probability of the cyclone being within the area at any of the subsequent warning times (at six hourly intervals) within the interval being considered. Figure 6 illustrates the results of this test. The predicted probabilities were classed into cells of 0–4.5%, 4.5% to 9.5%, etc. to 89.5% to 94.5% (no probabilities > 94.5 were forecast). The mean predicted probability and the mean observed frequency of strikes are shown for each time interval. The differences between observed and predicted mean values were tested (same binomial test as before) for statistical significance. 114 such tests were conducted (6 time intervals vs 19 cells); of these only four differences were found to be significant at the 5% level. No adjustment was made for dependence between cases since stratification into groups makes this a particularly difficult problem; however, an adjustment for dependence has the effect of reducing statistical significance in any case.

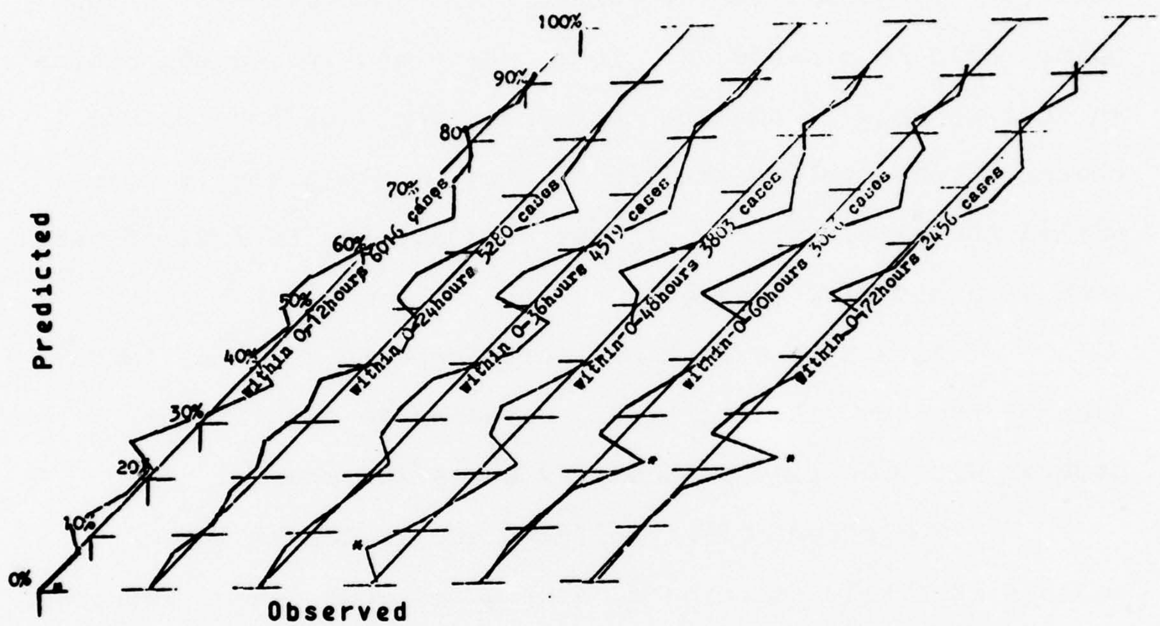


Figure 6. Comparison between observed strike frequency (abscissa) and forecast strike probability (ordinate). 45° line represents the "expected" for each of 6 progressively wider time intervals. Points represent the mean values for 5% wide intervals (0–5% etc.). (*) Differences in forecast probability and observed frequency of strikes is significant at the 5% level.

One aspect of the test results is worthy of comment, that is the general increase of both observed and forecast means in the 0-4.5% group. The mean predicted value rose from 0.1% within 0-12 hours to 1.3% within 0-72 hours. This is probably attributable to the criteria that only forecasts where the cyclone actually passed within 500 miles of a test point would be considered. Thus, there was introduced a bias in that we know in advance that there would be some random chance of the cyclone striking a test point (given it came within 500 miles) since our test area amounts to 1.6% of the area of a 500 mile circle.

With this exception, which appears to be a limitation of the test itself, test 3 revealed no significant problem with the time probability summation scheme.

The effect of stratifying the forecasts into classes as likely to be good, average or poor can be inferred from figure 7. The lines show the average observed frequency of strikes, and the forecast strike probability for the four groups of geographical points. The north group (see figure 5) is predominantly class 3 (difficult), the west group class 1 (easy) and the east group class 2 (average). The bases group may have representation from each class and the "all groups" set of lines is a composite of all four groups.

The difference between observed and forecast averages can be thought of as a bias or systematic error. The overall (all groups) average strike probability is essentially identical to the observed strike frequency. For comparative

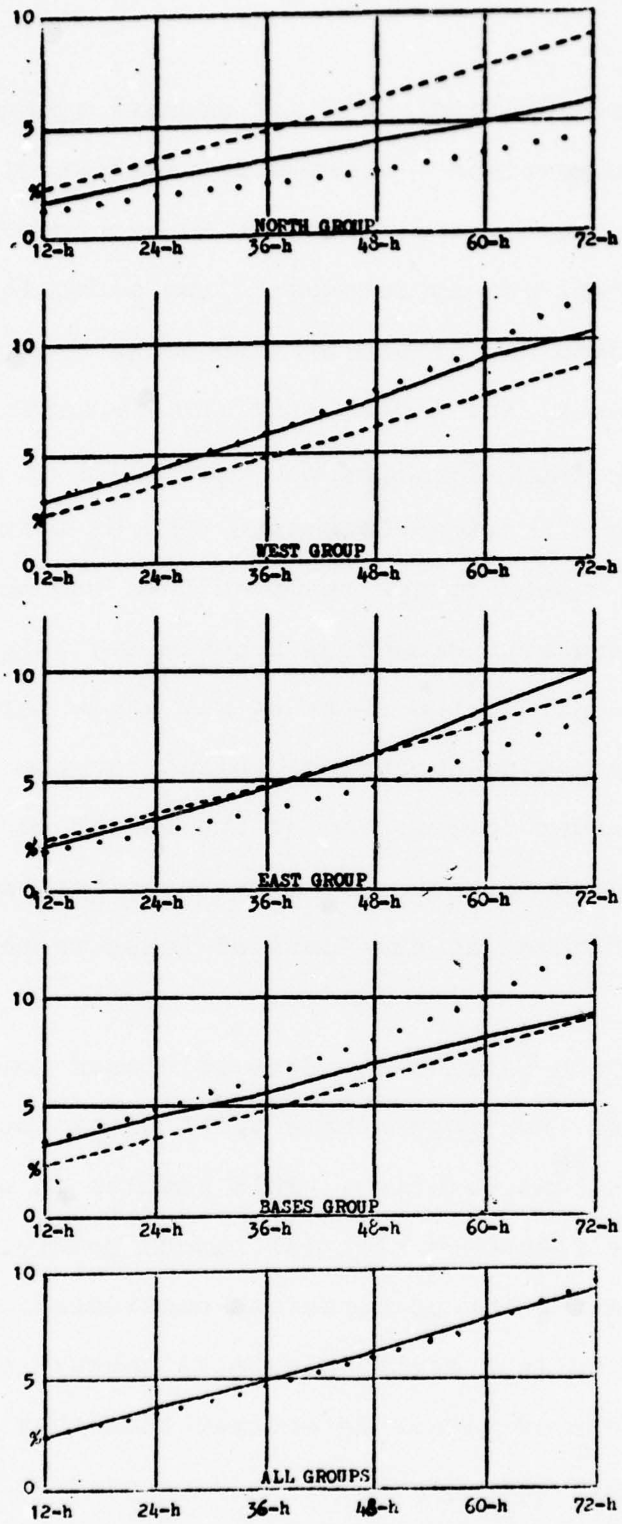


Figure 7. A comparison of average observed (• • •) strike frequency to average forecast strike (——) probability by groups (top to bottom) and by forecast interval (left to right). Shown also on the top four small graphs is the average strike probability forecast (- - -) for the combined groups (lower small graph).

purposes, we have plotted this "all groups" average forecast on each group comparison. Presumably, without classifying the forecasts, the average forecasts in each group would approximate the "all groups forecast" line since larger (smaller) standard deviations for the north (west) group decreases (increases) the probability that forecast points were near the actual track (hence within our 500 n mi circle).

Using stratified forecasts reduces systematic errors (solid line is closer to the observed than is the dashed line) for the north and west groups by roughly two thirds with a similar effect only in the short to mid range forecasts for the bases group and no appreciable effect on the east group.

The under forecasting of the threat to the group of actual bases seems to belie the contention that forecasters "aim" for major bases as the "path of least regret" (Simpson 1971).

As noted earlier the data is biased somewhat by the requirement that the cyclone have a CPA within 500 miles of the point under consideration. This results in a greater observed strike frequency than for random points. Notice that of those forecast-point combinations considered, 9.32% actually resulted in a strike within 72 hours; this is at least one or two orders of magnitude greater than that for a random point selection. This high-side bias means that the relevant portion (inside 500 n mi circle) of the distribution is biased toward the center. When compared to the average forecast error distribution, class 3 has much less density in the

center; class 1 has more. Therefore in this biased test the average should be a systematic overforecast for the class 3 dominated north group and an underforecast for the class 1 dominated west group with little or no bias in the predominately class 2 eastern group. This is generally what is observed and is again a consequence of the test rather than an inherent weakness in the system being tested.

4.0 Operational applications

The concept of operationally usable strike probability forecasts requires not only information sufficient to specify the probability density relative to center location, but also information as to the weather at various radial distances from the center. We addressed this subject with regard to 50 knot winds, i.e. if we know the distance (d) from the cyclone center to the 50 kt isotach, the probability of our point receiving winds of at least 50 kt is the probability of the cyclone passing within distance (d) of our point. This weather element (wind) was used because it is more familiar.

The most likely candidates for weather element or weather threat forecasts are the

1) Probability of winds in excess of some specified level(s).
2) Probability of seas in excess of some height(s).
3) Probability of total rainfall in excess of some value(s).
4) Expected rainfall rate.
5) Expected percent of time which ceiling-visibility combinations are below some minimums.
6) Probability of storm surge in excess of some height.
7) Probability of winds from a particular direction.

A key problem in all these is that, in some way, the value (or state) of the element must be expressible as a function of direction and distance relative to the moving

tropical cyclone.

As one example of such information, the JTWC tropical cyclone warning describes at times the radial extent of 30, 50, and 100 kt winds.

Another example involves the extent of seas in excess of some value. A newly developed program at the Naval Environmental Prediction Research Facility (NEPRF), TYWAVES (Brand et al. 1977), takes the Joint Typhoon Warning Center's (JTWC) warning and predicts the storm generated seas about the moving cyclone center. One or more contours of this pattern can be described by a series of ranges and bearings from the cyclone center. Thus a particular height of sea is expressible as a range and bearing from the cyclone center.

Atkinson and Penland (1967) devised a scheme to use climatology to estimate the resulting weather at a station, given that a tropical cyclone is at a particular range and bearing from the station. Using this technique, and knowing the probability of a cyclone being in a certain position, one can either predict the mean value of a weather element at the station or predict the probability of some value being exceeded. This technique has broad applicability to many weather elements, both in the general case (not unlike data compositing) for any overwater point and the local case about a particular base wherein local terrain influences are automatically considered.

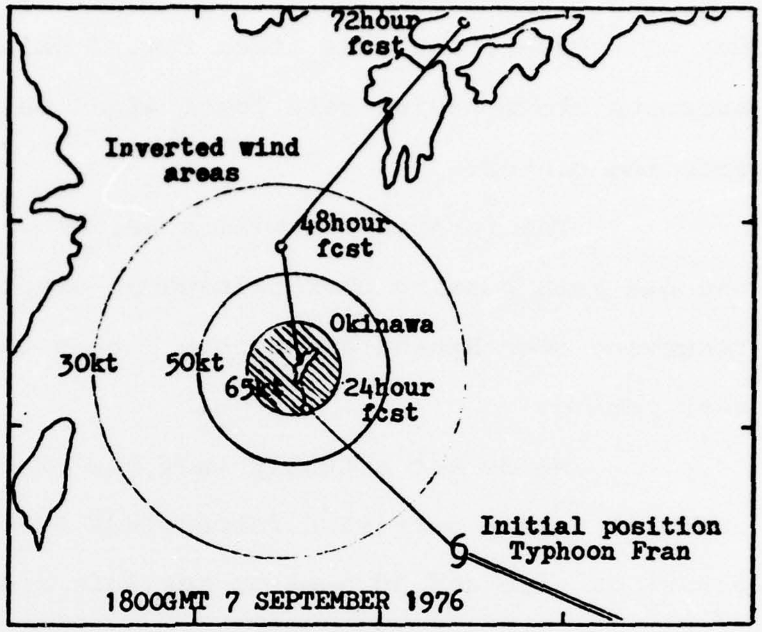
To illustrate the potential for operational applications, we will draw upon a particular example and look at winds only.

Example: On 7 September 1976, a supertyphoon Fran with winds in excess of 130 kt was moving across the Philippine Sea on a pre-recurvature track toward Okinawa. She was an enormous storm having gale force winds out to about 300 miles from the center.

The forecast we will consider was made at 1800 GMT and had Fran passing over Okinawa in about 30 hours and then recurving over Kyushu and Honshu within the three day forecast period.

We do not actually know the extent of winds in Fran, but will assume hurricane force winds extended to 75 n mi on her right side and 50 n mi on her left side, that 50 kt winds extended 150 miles on her right side and 125 on her left side. The latter are one half the extent of 30 kt winds given in the 1800 GMT forecast, which were assumed to be correct. We further have assumed this wind distribution would remain the same for the following 3 days.

Figure 8 illustrates these wind radii inverted about Okinawa. The inversion is because winds generally extend farther on the right side, hence we get the same effect with the typhoon farther away on the left than on the right. If our assumptions are correct and the typhoon passes within the inner shaded area, our point (Buckner Bay) receives at least 65 kt of wind. If the typhoon passes within the 50 kt limits (which also includes the inner area), then our point receives at least 50 kt winds. Similarly if the typhoon passes within the outer ring Buckner Bay receives at least 30 kt winds.



Inset table 1

time (hours)	65kt wind threat	50kt wind threat	30kt wind threat
0	<.5%	<.5%	<.5%
12	<.5	2	40
24	25	75	99
36	11	43	89
48	3	18	46
60	1	6	25
72	<.5	2	10

Inset table 2

within time (hours)	65kt wind threat	50kt wind threat	30kt wind threat
0	<.5%	<.5%	<.5%
12	<.5	8	55
24	28	82	99
36	37	88	>99.5
48	40	94	>99.5
60	42	96	>99.5
72	44	97	>99.5

Figure 8. An illustration of an actual forecast for typhoon Fran, 1800 GMT, 7 September 1976. The nested offset circles represent the 65 kt area of concern (inner area), 50 kt area of concern and the 30 kt area of concern (outer area) about Buckner Bay, Okinawa. The Inset tables show the estimated threat of 65, 50 and 30 kt winds either at specific hours (multiples of 12) after forecast time (inset table 1) or during a time period beginning at forecast time and ending some (multiple of 12) hours later (inset table 2).

The first Inset table of figure 8 shows the instantaneous probability of Fran being within either the 65, 50 or 30 kt wind areas at forecast time and at 12 hour intervals thereafter to 72 hours.

The second Inset table shows the time integrated probability of Fran being inside the wind areas at any time between 1800 GMT 7 September 76 and some later time given in 12 hour intervals. For example the probability of 65 kt at Buckner Bay within 48 hours is about 40% which is much larger than the probability of 65 kt at 48 hours after forecast time which was only 3%. This is because "within 48 hours" not only includes 0, 12, 24, 36 and 48 hours but also all the in-between times.

4.1 Conditions of readiness

Conditions of readiness indicate that the probability of winds of a certain force occurring within a specified time interval has reached some critical value.

Commonly Western Pacific Commanders use either 50 kt or 65 kt as the wind force which limits their most serious readiness condition. We will refer to these as Severe Storm (SS) or Typhoon (T) conditions. They also use a sequence of numbers determined by probability within a time period.

4 Force winds <u>possible</u> within 72 hours

3 Force winds <u>possible</u> within 48 hours

2 Force winds <u>expected</u> within 24 hours

1 Force winds <u>expected</u> within 12 hours

If we take the terms "possible" and "expected" to mean at least 5% and 50% respectively, then the inset tables of figure 8 suggest what conditions should be set, if not already in effect, at this time. Since we are interested in within (?) hours, we look at the time summed table (inset table 2).

For typhoon force winds, only the criteria for conditions 3 and 4 are met since the probability of 65 kt winds in 24 hours is only 28%, thus T3, the more severe, should be set.

For those commanders who use the "severe storm" condition, the critieria for conditions SS2, SS3, SS4 are met; thus condition SS2 should be set.

If there are evolutions which must be completed in winds under 30 kt, which may well include moving ships and aircraft, inset table 1 suggests they should be nearing completion at some time around 12 hours from forecast time. These are the type of activiites typically completed in condition T2, thus the prudent commander may want to set condition T2 at this time even if his probability criterion of typhoon force winds was not met. There are many practical considerations in setting conditions, but information such as that contained in the inset tables appears to be a valuable supplement to that decision process.

Figure 9 illustrates contours of all points for which the minimum criteria (as interpreted above, i.e. 5%, 50% rule) for the typhoon conditions of readiness are met. All points within the outer curve have at least a 5% probability

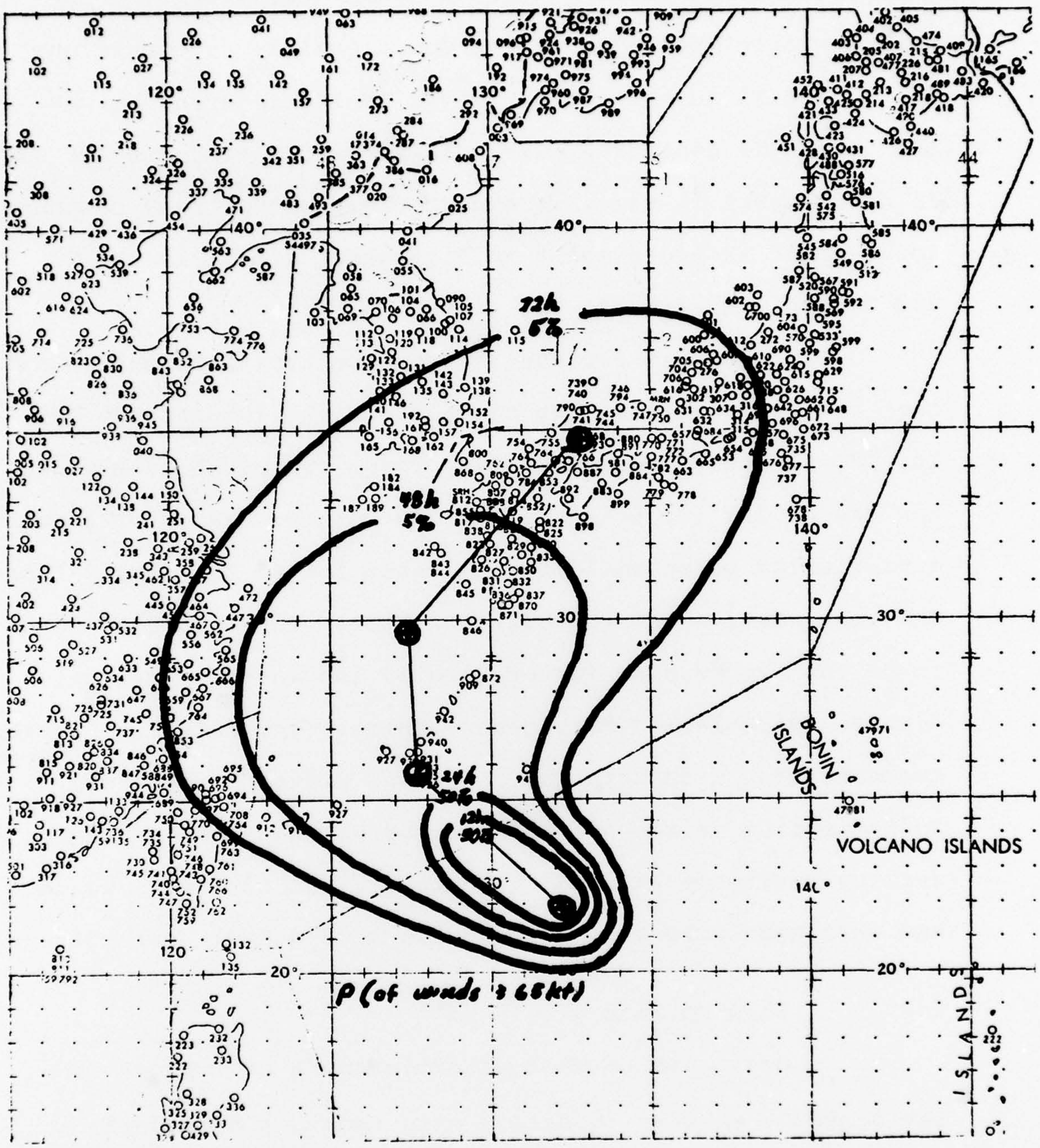


Figure 9. Based on the same forecast as in figure 8. Contours of points whose probability of typhoon force winds equal: inner contour, 50% within 12 hours; 2nd contour, 50% within 24 hours; 3rd contour 5% within 48 hours; outer contour, 5% within 72 hours.

of typhoon force winds within 72 hours (condition T4) and points within the inner curves would qualify as conditions T3, T2 and T1 respectively. There is little space between the T1 and T2 contours. Since these were intended to be set 12 hours apart in time, we expect their along track contours to be about 12 hours apart in distance. Similarly the T2 and T3 contours are too far apart.

Figure 10 represents the same type information except the probabilities are now to 5%, 10%, 20% and 33% for T4, T3, T2 and T1 respectively. These represent overwarning factors of 20, 10, 5 and 3. An overwarning factor of 3 means a particular point would brace itself for 65 kt winds 3 times and only observe their occurrence once. Three is considered to be the overwarning factor used by the National Weather Service for Atlantic hurricane warnings (Sugg 1967). Private communication with National Hurricane Center forecasters indicate five is the approximate overwarning factor used for setting hurricane watches. To some extent hurricane watches and warnings correspond to conditions T2 and T1 respectively.

4.2 Ship routing

Again let us look at our example of Typhoon Fran. Let's assume we want to sail a ship from one of several points and we can make 20 kt. Maximum speed may be reduced, of course, in high winds and seas. Let's further assume that 50 kt winds and the seas that accompany such winds are the upper limit for safe operating conditions, and we want to be 95% confident of staying out of 50 kt winds. Figure 11 gives

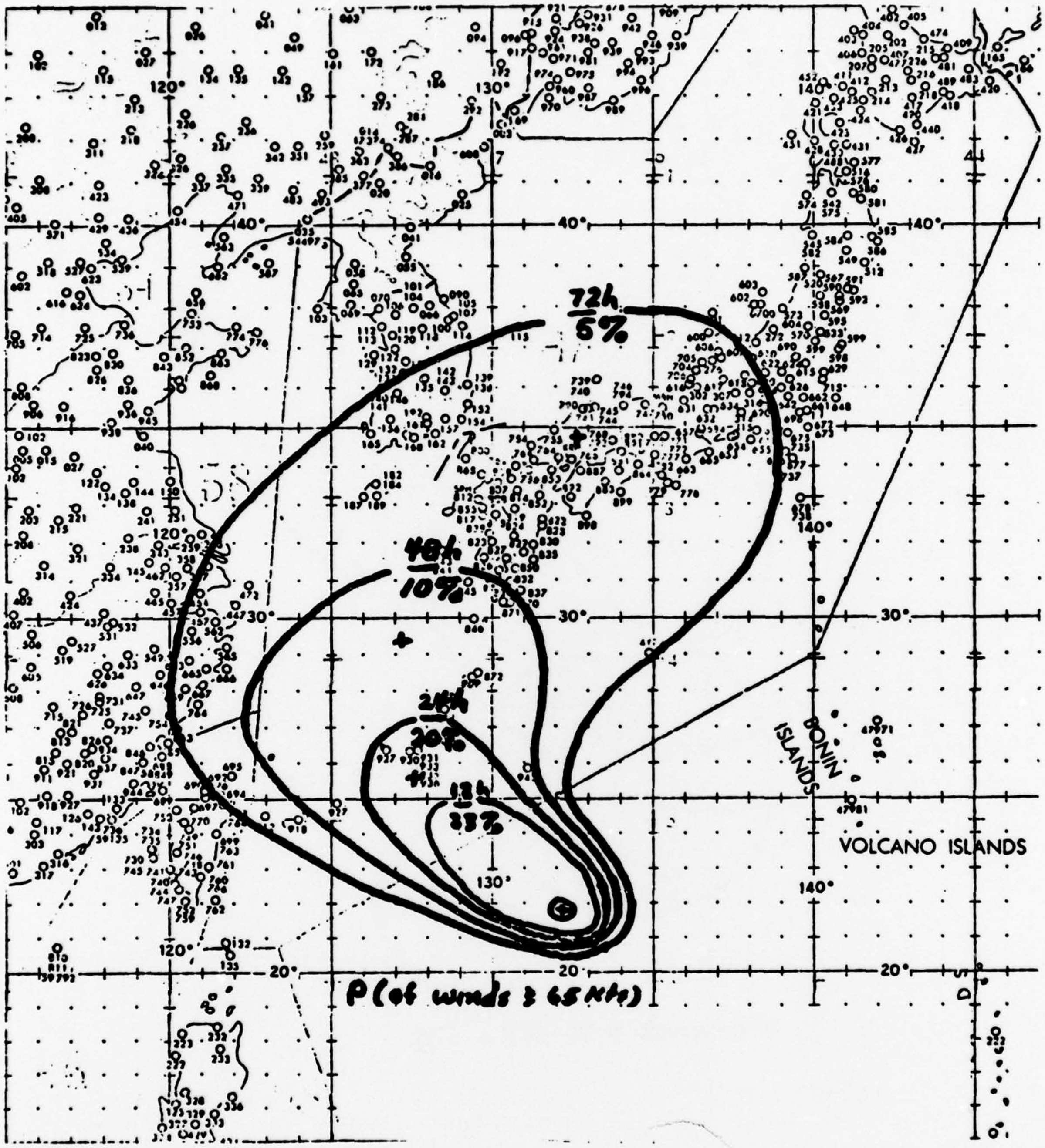


Figure 10. Same as figure 9 except contour values inner to outer are 33% within 12 hours, 20% within 24 hours, 10% within 48 hours and 5% within 72 hours (the latter is unchanged).

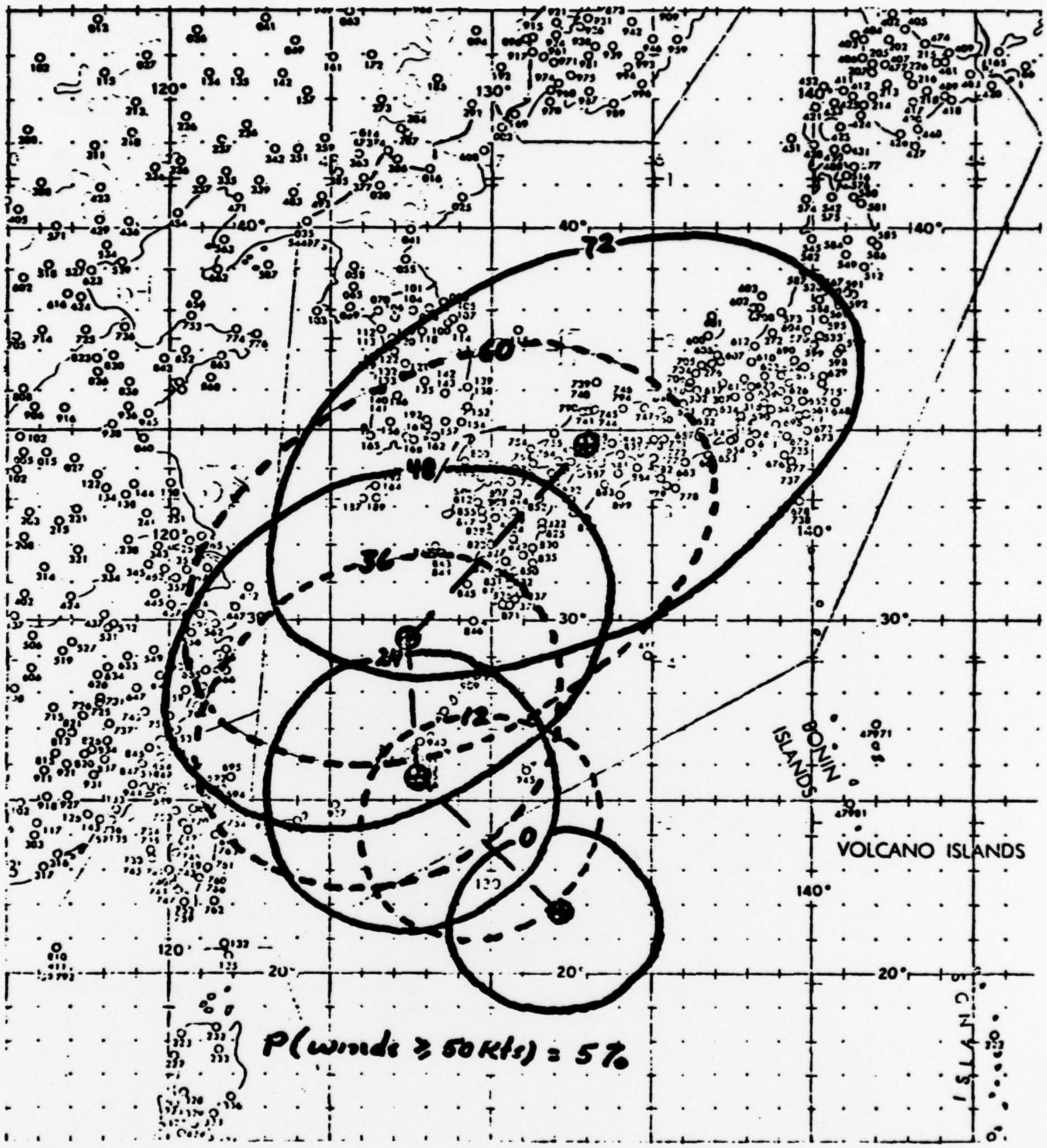


Figure 11. Based on the same forecast as in figure 8. Contours of 5% probability of 50 kt winds at multiples of 12 hours (odd multiples of 12 h are dashed).

contours of 5% probability of 50 kt (or greater) winds at 12 hour intervals from 0 to 72 hours.

For example a ship in Buckner Bay (not a safe haven Brand and Blelloch, 1976) can minimize the probability of 50 kt winds by running either southwest of northeast. Southwest is probably preferable because of following winds and seas. To stay ahead of the approaching 5% contours, the ship would have to maintain about 13 kt if it started out at 1800 GMT. This seems to clearly suggest that for the ship in Buckner Bay, the optimal decision time has already passed. Another typical problem is a ship partway to Kaohsiung from Sasebo. For those south of $27\frac{1}{2}^{\circ}$N continuing south at best speed is clearly indicated. For those north of 31°N or so returning to Sasebo (a safe haven) seems clearly indicated since in 24 hours they will otherwise be in an area with an unacceptably high probability of 50 kt winds. Those between 27 1/2 and 31° are faced with a difficult choice between the southward "crossing the T" and trying to run upwind back to Sasebo.

For ships heading Sasebo to Yokosuka, or back one can set up similar problems. In each case this kind of information helps to crystalize one essential element of the problem.

It is probably worthwhile to mention that evasion is a continuing problem. The complications reappear with each 6-hourly warning and the final solution to the problem is at hand only when the final threat is gone.

4.3 Disaster control

In many cases it is the responsibility of a senior military officer (i.e. U. S. Armed Forces Area Commander) to plan for and coordinate disaster assistance in a large political area, such as Japan, Korea, Philippines or Taiwan. In these cases it is useful for him to know the probability of a disaster at some point under his jurisdiction without yet knowing the identity of the actual points involved. In the example, Fran posed a real threat to Japan from the Ryukyus to Tokyo with the major threat to Okinawa and Kyushu. As it happened the major damage was in Kyushu. It is possible to prepare strike probability information as the probability that a typhoon will strike (or that 50 kt, 65 kt, etc. winds will be felt) somewhere within a country, province or other political subdivision within specified time intervals after warning. This kind of information is valuable in alerting forces that would be involved in disaster relief or recovery operations should a disaster occur within a bounded region.

5.0 Summary and recommendations

The concept of strike probability has been demonstrated in a limited application for test purposes on 1976 JTWC forecasts. These test results indicate the concept as designed and engineered is sound. Based upon these test results, field testing was recommended and is presently underway.

Since the concepts involved in strike probability forecasting are somewhat difficult, it is imperative that an attempt be made to explain the concepts by limited distribution written material (such as user's manual). The effectiveness of that attempt should be evaluated by post season interviews with user personnel, before further dissemination. The operational applications for strike probability information should be pursued. Many of the envisioned applications involve a map type display which is adaptable to a NEDS type system.

The most economical method of mapping probability is by considering a grid of points representing non-overlapping areas. Then to compute the probability of being within an area about each point, one must only extract and sum an appropriate portion of the probability stored at surrounding grid points. This mechanism should be developed. Another area of recommended development is the general area of joint probabilities of some condition versus tropical cyclone position. As discussed previously, the probability

of a point receiving at least 50 kt winds is dependent jointly upon the horizontal extent of 50 kt winds and center position. These joint probabilities must be conditioned on the known forecast and factors such as land/water distribution, latitude, etc. A study to determine these conditional probabilities is a fundamental step in the development of such predictions. Until such probabilities are understood, it is necessary to assume that the predicted radius of 50 kt winds will either verify, or represents an unbiased mean value wherein the actual radius is equally likely to be greater or less by a certain distance. In the range of typical values of this radius, this assumption may be acceptable, but near the extremes (i.e., zero) it clearly is unrealistic.

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